

Energetic neutrinos from the Sun and Earth and dark matter substructure

Savvas M. Koushiappas^{*} and Marc Kamionkowski[†]

^{*}*Department of Physics, Brown University, 182 Hope St., Providence, RI 02912, U.S.A.*

[†]*California Institute of Technology, Mail Code 350-17, Pasadena, CA 91125, U.S. A.*

Abstract. Dark matter halos contain a wealth of substructure in the form of subhalos and tidal streams. Enhancements in the dark matter density of these regions leads to enhanced rates in direct detection experiments, as well as enhanced dark matter capture rates in the Sun and the Earth. Direct detection experiments probe the present-day dark matter density, while energetic neutrinos probe the past history of the dark matter density along the solar system's orbit about the Galactic center [1]. We discuss how an elevated energetic neutrino flux can be used to probe the level of substructure present at the Galactic radius of the solar system.

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INTRODUCTION

One of the experimental probes of the nature of dark matter is the possible detection of high-energy neutrinos from the Sun and the Earth [2, 3]. If the dark matter particle is a Weakly Interacting Massive Particle (WIMP) [4, 5], then interactions between WIMPs in the Milky Way halo and nuclei in the Sun/Earth can reduce the speed of the WIMPs so that they get captured by the gravitational potential well of the Sun/Earth. As the accumulation of WIMPs increases in the solar interior, so does their annihilation rate. Final state neutrinos from WIMP annihilation escape the Sun, and travel freely to the Earth (similarly, neutrinos from the center of the Earth travel to the surface) where they may get detected in a high energy neutrino experiment such as IceCube [6]. The expected rate of high energy neutrinos depends on the rate at which WIMPs are gravitationally captured (i.e., the dark matter density), and the rate at which they are depleted by annihilation.

Direct detection of dark matter (e.g. in a liquid noble gas [7]) probes the present day dark matter density at the solar galactic radius. Therefore, the rate in a direct detection experiment is proportional to the rate of high-energy neutrinos from the Sun/Earth [8]. However, the proportionality is time independent only if the dark matter density is time independent. The presence of Galactic substructure [9, 10, 11] suggests that the constant of proportionality can change with time, depending on the *past history* of the dark matter density along the Sun's orbit about the Galactic center. As such, it may be possible to probe Galactic substructure using future measurements of the flux of energetic neutrinos from the Sun/Earth and direct detection experiments [1]. In this proceedings we summarize these effects, and discuss how future measurements can be used to probe Galactic substructure.

ENERGETIC SOLAR NEUTRINOS FROM THE SUN AND EARTH

The classical case

In the standard scenario, the flux of upward muons from WIMP annihilation in the Sun is

$$\begin{aligned} \Gamma_{\nu,0} = & 7.3 \times 10^5 \text{ km}^{-2} \text{ yr}^{-1} \left(\frac{N}{N_{\text{eq}}} \right)^2 \left(\frac{\rho_\chi}{0.3 \text{ GeV cm}^{-3}} \right) \left(\frac{m_\chi}{100 \text{ GeV}} \right)^2 \\ & \times \left(\frac{\sigma}{10^{-40} \text{ cm}^2} \right) \left[\frac{\xi(m_\chi)}{0.1} \right] f(m_\chi) \end{aligned} \quad (1)$$

while the corresponding flux from the Earth is obtained by replacing the prefactor of Eq. (1) by $15 \text{ km}^{-2} \text{ yr}^{-1}$. Here, m_χ is the mass of the WIMP, ρ_χ is the dark matter density and σ is the WIMP-nucleon scattering cross section. The function $f(m_\chi)$ varies over the range $5 \leq f(m_\chi) \leq 0.5$ over the mass range $10 \leq m_\chi/\text{GeV} \leq 1000$ for the Sun (with a slightly larger range for the Earth), while the function $\xi(m_\chi)$ is in the range $\sim 0.01 - 0.3$ over the same mass range.

The factor N/N_{eq} is the number of WIMPs in the Sun/Earth, and it is set by the competing effects of WIMP capture and annihilation. If we assume the capture rate is C_c and the annihilation rate is C_a , then the time t evolution of the number N of WIMPs is given by the differential equation,

$$dN/dt = C_c - C_a N^2. \quad (2)$$

If both, C_c and C_a are constant with time, and the initial condition is $N(t=0) = 0 \equiv N_0$, the solution to this equation is

$$N(t) = \sqrt{\frac{C_c}{C_a}} \frac{e^{t/\tau} - \gamma e^{-t/\tau}}{e^{t/\tau} + \gamma e^{-t/\tau}}, \quad (3)$$

where

$$\gamma \equiv \frac{1 - N_0 \sqrt{C_a/C_c}}{1 + N_0 \sqrt{C_a/C_c}} \leq 1, \quad (4)$$

and $\tau = 1/\sqrt{C_c C_a}$ is the equilibration timescale. After a time $t \gtrsim \tau$, the number N approaches $N_{\text{eq}} \equiv N(t \gg \tau) = \sqrt{C_c/C_a}$, and the annihilation rate Γ_ν becomes equal to (one half) the capture rate, $\Gamma_\nu = C_a N^2/2 = C_c/2$.

The equilibration timescale is determined solely by the capture and annihilation rates C_c & C_a , and thus set by the cross section of the WIMP-nucleon scattering, and the cross section for WIMP annihilation. Its value is given by (for the Sun)

$$\begin{aligned} \tau_\odot = & 1.9 \times 10^5 \text{ yrs} \left[\left(\frac{\rho_\chi}{0.3 \text{ GeV cm}^{-3}} \right) \left(\frac{\langle \sigma_{A\nu} \rangle}{10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right) \right]^{-1/2} \\ & \times \left(\frac{m_\chi}{100 \text{ GeV}} \right)^{-3/4} \left(\frac{\sigma}{10^{-40} \text{ cm}^2} \right)^{-1/2}, \end{aligned} \quad (5)$$

while the corresponding value for the Earth can be obtained by replacing the prefactor of Eq. 5 by $1.1 \times 10^8 \text{yr}$. In Eq. 5 $\langle \sigma_{Av} \rangle$ is the thermally-averaged annihilation cross section (times relative velocity v in the limit $v \rightarrow 0$). Typically, the equilibration timescale for the Sun is smaller than the age of the Solar System. The equilibration timescale for the Earth is generally much higher mainly due to differences in mass and composition. It should be noted that in general, equilibration timescales may vary by numerous orders of magnitude, not only due to the current uncertainties in the WIMP physics, but also due to some potentially more exotic physics such as Sommerfeld [12] or self-capture [13] enhancements.

The rate in a direct detection experiment is given by,

$$R_{\text{DD}}^{\text{sc}} = 2.2 \times 10^5 \text{kg}^{-1} \text{yr}^{-1} \left(\frac{\rho_\chi}{0.3 \text{GeVcm}^{-3}} \right) \eta_c(m_\chi, m_i) \left(\frac{m_\chi}{100 \text{GeV}} \right) \times \left(\frac{m_i}{100 \text{GeV}} \right) \left(\frac{m_i}{m_\chi + m_i} \right)^2 \left(\frac{\sigma}{10^{-40} \text{cm}^2} \right), \quad (6)$$

where m_i is the mass of the target nucleus, and $\eta_c(m_\chi, m_i)$ (given in Ref. [14]) accounts for form-factor suppression. Comparison between Eqs. 1 & 6 shows that a measurement of the two rates gives a measure of the quantity N/N_{eq} . If the dark matter halo density is constant with time, and the equilibration timescale is shorter than the age of the Solar System, then $N = N_{\text{eq}}$ and the two rates are proportional to each other (modulo the microphysics that describes each process). If on the other hand the dark matter halo density is time dependent (for example the dark matter density was higher at some time in the past), then the neutrino signal will be elevated relative to the direct detection signal.

Time-dependence of the capture rate

If there is Galactic substructure at the solar Galactic radius ($\sim 8.5 \text{kpc}$), then the dark matter density at the position of the Solar System varies with time. Due to the time lag between capture and annihilation, the current energetic neutrino flux is determined not by the present local dark matter density, but rather the density of dark matter along the past trajectory of the Solar System. On the other hand, the current direct detection rates in a direct detection experiment are determined by the present local dark matter density. In general, the behaviour of the energetic neutrino signal can be obtained by numerically solving Eq. 1 with a time dependent capture rate. Instead, we can glean the behaviour of time dependence of the capture rate by considering some simple instructive toy examples.

Consider the passage of the Solar System through a region where the density is enhanced by a factor of ~ 100 relative to the smooth density at the Solar Galactic radius, and that the duration of this enhancement is of order $\sim 10^7$ years (e.g., a $10^9 M_\odot$ halo of constant density). The left panel of Fig. 1 shows the effects on the capture rate, direct detection rate and energetic neutrino signal for this toy interaction. The direct detection rate is directly proportional to the dark matter density and thus traces the capture rate.

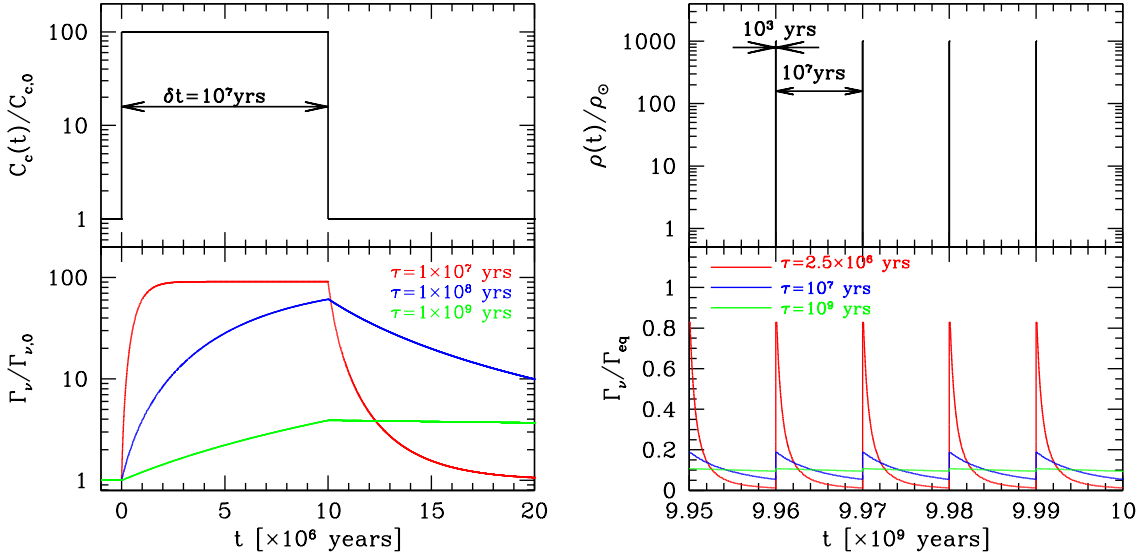


FIGURE 1. *Left:* The effect of a time dependent capture rate to the energetic neutrino signal from the Sun (red curve) and the Earth (green curve). The top panel shows the capture rate (proportional to the direct detection rate). The bottom panel shows the energetic neutrino flux for three different values of the equilibration timescale. *Right:* The effect of multiple interactions. Line types same as figure on left. Both figures adapted from [1].

However, the energetic neutrino signal enhancement is not instantaneous, but rather is set by the equilibration timescale. Short equilibration timescales relative to the duration of the capture rate enhancement in this example (e.g. the Sun) result in a fast neutrino enhancement, while long equilibration timescales (e.g. the Earth) result in a lagging signal enhancement. After exiting such a region of capture rate enhancement, the direct detection signal (capture rate) will return to the canonical value, the signal from the Sun will return to the canonical value at some later time set by the short equilibration timescale, but the signal from the Earth will remain elevated. A measurement of such elevated signal will then point to a recent passage through a high-density region of dark matter in the recent past of the Solar System's history.

It is interesting to consider the case where there are multiple interactions with regions of enhanced capture rate (e.g., passage through numerous small scale subhalos). If the timescale between successive encounters is shorter than the equilibration timescale of the Sun/Earth, then it is possible the signal of energetic neutrinos to remain elevated at all times. For the purpose of illustration, the right panel of Fig. 1 shows the effect of having multiple successive signal enhancements that would correspond to the presence of $1M_{\odot}$ objects at the solar Galactic radius [11] (for example if all the local dark matter density was in objects of mass $1M_{\odot}$). The mean timescale between interactions would be $\sim 10^7$ years, the duration of each interaction would be $\sim 10^3$ years, and the corresponding capture rate enhancement would be ~ 1000 . In this case, for equilibration timescales which are of order the mean timescale between encounters, the energetic neutrino signal is depleted completely prior to the next encounter, while for longer equilibration timescales, the net effect is an elevated signal at all times. In terms of

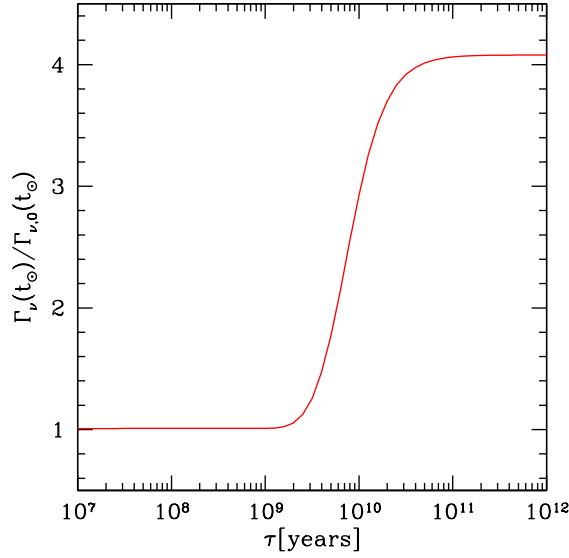


FIGURE 2. The net effect of the presence of a population of $10^{-6}M_{\odot}$ objects in the Milky Way halo. For long equilibration timescales, the energetic neutrino signal is higher than the signal that would be obtained from a smooth-only dark matter distribution.

the signals from the Sun and the Earth, this means that the signal from the Earth will be boosted relative to the signal from the Sun for most of the time.

The presence of substructure effectively speeds up equilibration if the equilibration timescale is larger than the age of the solar system. For example, suppose that the dark matter has some smooth component, and a substructure population that extends all the way down to the smallest scales that correspond to cold dark matter particles [11], consistent with an extrapolation of the substructure mass function found in numerical simulations [15, 16]. If we only consider objects of mass $10^{-6}M_{\odot}$, i.e., a mean density enhancement of ~ 100 with duration of 50 years, and a frequency of one per million years, then for long equilibration timescales (longer than the age of the Solar System) the amount of depletion of WIMPs is negligible relative to the amount of WIMPs being captured. This effect leads to a continuous buildup of WIMPs, i.e., an energetic neutrino signal that today is higher than the signal that would be obtained if the Milky Way halo was smooth. Fig. 2 shows this effect as a function of the equilibration timescale. Long equilibration timescales result in a net build-up of WIMPs. Therefore, as N approaches N_{eq} faster over a given timescale (e.g., the age of the solar system) due to substructure, the equilibration of a WIMP population is sped up.

CONCLUSIONS

We show that the presence of substructure in the Milky Way halo alters the energetic neutrino signal expected from the Sun and the Earth. A future measurement of the direct detection rate in dark matter experiments, and the rate of energetic neutrinos from the Sun/Earth can be used as a probe of the amount of substructure in the Milky Way. In

addition, the comparison between the energetic neutrino signals from the Sun and the Earth can yield information on the recent past history of dark matter density at the solar Galactic radius and the Solar System's dark matter encounters in its past.

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